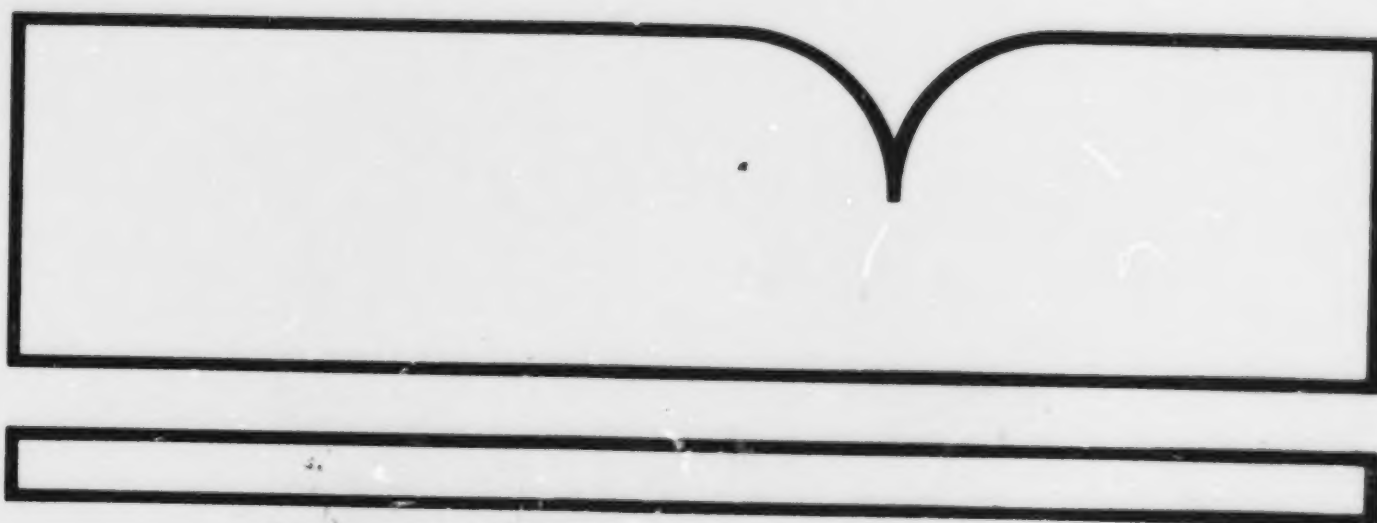


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EPA MODEL DEVELOPMENT FOR STABLE PLUME IMPINGEMENT ON
ELEVATED TERRAIN OBSTACLES

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ABSTRACT

The U.S. Environmental Protection Agency's Complex Terrain Model Development program is designed as a series of progressively advanced model development efforts accompanied by requisite field studies to provide data for model evaluation. Plume impingement studies have been performed during 1980 at Cinder Cone Butte near Boise, Idaho, and during 1982 at Hogback Ridge near Farmington, New Mexico. Experimental protocol consisted of terrain-surface measurements of dual-tracer plumes emitted from mobile cranes during stable atmospheric conditions. Dimensions of simultaneously-released oil fog plumes were obtained prior to impingement by lidar and by time exposure photographs. Accompanying meteorological sensors included instrumented towers, tether sondes, monostatic and Doppler acoustic sounders, and optical crosswind anemometers.

Selected data from the Cinder Cone Butte study were initially used to evaluate the performance of two new preliminary algorithms (Neutral and Impingement) and of four existing complex terrain plume dispersion models (Valley, Complex I, Complex II, and Potential Flow Model). After a case study analysis to

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improve understanding of the physical processes involved, the Neutral and Impingement models were refined into the Lift and Wrap models, respectively. Currently, the Lift and Wrap components have been combined to form the basis of the Complex Terrain Dispersion Model which has now been evaluated on all of the Cinder Cone Butte data and on selected hours of Hogback Ridge data. Simultaneous scaled physical modeling is being performed to determine proper similarity criteria and limits of applicability for fluid modeling simulations of plume-terrain interactions.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is currently sponsoring the Complex Terrain Model Development (CTMD) program, a multi-year integrated program to develop and evaluate practical plume dispersion models for calculating ground-level air pollutant concentrations that result from large emission sources located in mountainous terrain. The initial focus of the CTMD program is to develop models with known accuracy and limitations for simulating one-hour-average ground-level concentrations during stable atmospheric conditions.

The objectives of the CTMD program were described by Holzworth (1980) and are based on recommendations arising from an EPA-sponsored workshop to consider the issues and problems of simulating air pollutant dispersion in complex terrain (Hovind et al. 1979). In response to the workshop, the EPA initiated a program emphasizing the production of a useful model (or models) with demonstrated reliability and prescribed applicability. During the requisite field measurements and laboratory experiments, the observational needs of the modelers were to be foremost in importance. As described by Holzworth (1980), the CTMD program was perceived as an integrated and highly coordinated effort that involves:

- dispersion model development/evaluation/improvement,
- scaled physical modeling in a fluid modeling laboratory,
- field measurements/experiments centered on isolated terrain features, and
- field measurements/experiments centered on an existing power plant in terrain with opportunities for plume impingement and other types of plume-terrain interactions.

The CTMD program was begun in June 1980. The first major component was a field study conducted during the fall of 1980 at Cinder Cone Butte (CCB), a roughly axisymmetric, isolated 100-m tall hill located in the broad Snake River Basin near Boise, Idaho. The field study consisted of 10 flow visualization (oil fog) experiments and 18 multi-hour dual-tracer gas (SF_6 and CF_3Br) and oil fog experiments conducted during stable flow conditions with supporting meteorological, lidar, and photographic measurements.

The CCB data were used to develop and evaluate two new preliminary modeling algorithms (Impingement and Neutral) and to evaluate the performance of current EPA complex terrain plume dispersion models (Valley, Complex I, Complex II, and Potential Flow Model). The Impingement Model simulates dispersion during strongly stable flows in which plumes remain approximately horizontal and impinge on and travel around the sides of CCB. The Neutral Model simulates dispersion during slightly stable and neutral flows in which plumes rise over CCB. For the initial CCB model evaluations, 45 hours were selected from 153 case hours obtained during the 18 tracer experiments. The meteorological and tracer data were used in a "hands-off" mode; no modifications were made to the algorithms to improve their predictions.

The EPA CTMD First Milestone Report - 1981 (Lavery et al. 1981) describes the air quality models that were evaluated, the evaluation methods, and overall model performance. The report also provides comparative statistics of the model evaluations and summarizes the CCB field experiments and associated quality assurance activities. A series of experiments (Snyder and Lawson 1981) conducted in the EPA Fluid Modeling Facility water channel towing tank to quantitatively simulate the field studies are described in an appendix. The participation of the Fluid Modeling Facility is an integral part of the CTMD program, with the aim of determining proper similarity criteria and limits of applicability for fluid modeling simulations of plume-terrain interactions.

The CCB tracer gas source data (emission rates, locations and heights of tracer and oil fog releases), concentration data (over 12,000 bag samples) and meteorological data (from six towers, a tethered sonde and pilot balloons) were subsequently delivered to the EPA, and are available upon request.

The Second Milestone Report - 1982 (Strimaitis et al. 1982) documents subsequent work to improve the Impingement and Neutral modeling approaches, to refine the CCB meteorological and tracer gas data bases, and to further analyze the data to relate plume behavior and observed meteorological conditions. Unlike the

previous hands-off evaluations, the approach taken in this report is a case study analysis. From the 45 hours used in the initial model evaluation, 14 hours were selected for detailed individual case study to illustrate and contrast various flow situations and ranges of model performance.

This Second Milestone Report also contains, as an appendix, a paper prepared by the EPA Fluid Modeling Facility (Snyder et al. 1982). The paper describes a series of wind tunnel and towing tank experiments designed to study various aspects of stratified, sheared flow over a variety of simple obstacles, as well as flow over a scale model of CCB. In particular, the dividing-streamline concept is evaluated for obstacles of differing aspect ratio embedded in stably stratified flows, both with and without wind shear; and the effects of hill slope and wind shear on the flow patterns are discussed. On the basis of these experiments, the dividing-streamline concept was found to be applicable for a wide variety of terrain obstacles and stratifications.

In January 1982, the second phase of the CTMD program was initiated. This component included continuing model development and evaluation with the CCB data and performance of a second plume impingement study at the Hogback Ridge (HBR) near Farmington, New Mexico. The information collected at the HBR has enlarged the modeling data base to include measurements of flows and tracer gas concentrations in the vicinity of a long ridge.

MODELING STABLE FLOW CONDITIONS

The modeling of tracer gas concentrations measured at CCB is based on the concept of two distinct regimes of flow encompassing the hill (Figure 1). In Region 1, which extends from the base of the hill to a height H_c , the flow does not have enough kinetic energy to go over the hill and remains roughly horizontal as it goes around the hill. In Region 2, which lies above the dividing streamline that separates the two regions, the flow has enough energy to pass up and over the hill. The concept of the critical dividing streamline height, $H_c \equiv H(1 - Fr_H)$, is related to the notion that a fluid parcel can rise only through a height U/N , where H is the hill height, $U(H)$ is the wind speed at $z = H_c$, $N(z)$ is the local Brunt-Vaisala frequency defined by

$$N(z) = [g/\theta(z) (\partial\theta/\partial z)]^{1/2}, \quad (1)$$

g is the acceleration due to gravity, θ is the potential temperature ($^{\circ}K$), and Fr_H (the Froude number) is defined as

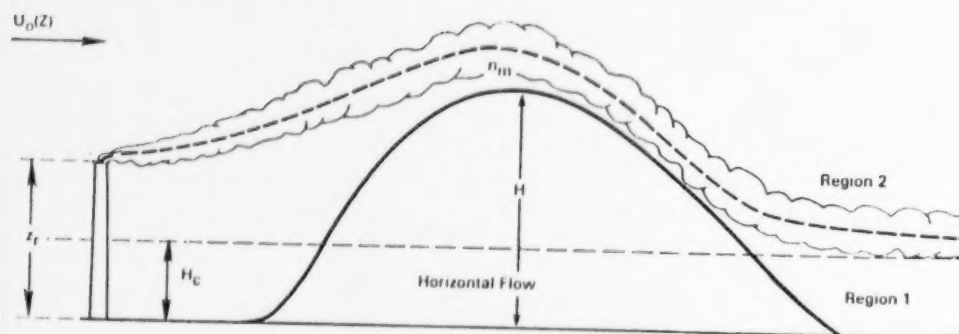


Figure 1. Schematic Diagram of Plume Behavior in Stable Flows Around Obstacles.

$$Fr_H \equiv U_0/NH. \quad (2)$$

If the wind speed and stratification are functions of height (as is generally the case), H_c is implicitly defined as follows

$$\frac{1}{2} U_0^2(H_c) = \int_{H_c}^H N^2(z)(H-z)dz. \quad (3)$$

The left-hand side of Equation 3 is the kinetic energy of the fluid at $z = H_c$, and the right-hand side is the potential energy gained by the fluid in rising through the height $H - H_c$.

The preliminary algorithms to simulate the flow in Region 1 and 2 were described in the First Milestone Report and by Venkatram et al. (1982). Model improvements and further model testing were discussed in the Second Milestone Report. The improvements to the Region 1 Impingement flow model (now termed the Wrap Model) included;

- use of an observed wind direction distribution function (Hanna 1983) instead of an assumed Gaussian distribution,
- ability to calculate concentrations at hill elevations near the release elevation instead of just at the stagnation point, and
- a new method for estimating σ_z (Venkatram et al. 1983).

The improvements to the Region 2 Neutral flow model (now termed the Lift model) included:

- modeling the air flow below H_c as a "dead" layer,
- generalizing the model by calculating the radius of curvature based on hill shape,
- use of an observed wind direction distribution function, and
- a new method for estimating σ_z (Venkatram et al. 1983).

As described by Strimaitis et al. (1983), the refined versions of the Neutral and Impingement models (referred to as the Lift and Wrap models, respectively) have been combined to form the basis of the Complex Terrain Dispersion Model (CTDM). The CTDM has been subsequently tested on all 153 hours of CCB tracer data and, for an initial assessment of the model's performance at a ridge, on 17 selected hours of HBR tracer data. The results of this latest model evaluation are contained in the draft Third Milestone Report - 1983 (Lavery et al. 1983). Also presented in this report are comparisons of laboratory simulations of neutral plume dispersion over CCB with field measurement data, as performed by the EPA Fluid Modeling Facility.

CCB CASE STUDY ANALYSIS

Fourteen case hours were selected from the 45 CCB hours discussed in the First Milestone Report. The concurrent SF_6 , CF_3Br , meteorological, and photographic data, and various model sensitivity calculations were analyzed in detail to gain a better understanding of the relationships among emissions, observed meteorological conditions, and measured concentrations in order to improve the model formulations. In addition, the 45-hour subset of the CCB data base was analyzed to develop systematic relationships between the plume observations and other measurements to help in the modeling effort. The specific analyses included:

- a comparison of vertical plume growth (σ_z) estimated from photographs with σ_z estimated from turbulent intensity measurements,
- a comparison of σ_z estimated from photographs with σ_z estimated from lidar data,
- a comparison of σ_y and σ_z estimated from lidar data with σ_y and σ_z estimated from turbulent intensity measurements,
- time series and spectral analyses of wind speed data to determine time scales of turbulence, and

- analysis of 5-min temperature data to estimate the vertical distribution of isentropic surfaces as surrogates for the streamline patterns over CCB.

The principal conclusions from the CCB case study and data analysis are:

- A plume released above H_c tended to travel over the hill. The plume path appeared to be consistent with streamlines in weakly stratified flow, as described both in theory and laboratory experiments.
- A plume released well below H_c tended to impinge and flow around the hill, lacking sufficient kinetic energy to surmount the hill.
- A plume released very near H_c tended to travel directly towards the hill, with only slight-to-moderate vertical displacement.
- When the vertical velocity gradient near release height in the approach flow was large and positive, the maximum concentration on CCB was often measured at an elevation lower than the release height due to downward plume deflection.
- When Fr_L ($\equiv U_o/NL$) based on the hill half-length was close to unity, lee side plume depression was observed at CCB.
- $\sigma_y \sim i_y x$, when i_y is measured near the release elevation.
- $\sigma_z \sim \sigma_w t / (1 + Nt/p)^{1/2}$, where $p = 0.5$ and $t = x/U_o$.
- U_o/N small is a necessary but not sufficient condition for large values of σ_y .
- The isentropic analyses suggest that the air flow below H_c can be treated as a "dead" layer and that flows above H_c can be considered approximately neutral.
- The model improvements result in better agreement between model calculations and observations. The use of the observed wind distribution function is especially important for wind speeds less than 3 m/sec.
- Meteorological measurements need to be taken as close to the source as is practical because of spatial and temporal inhomogeneities produced by slow mesoscale meanders and vertical shear.

THE HOGBACK DISPERSION EXPERIMENT

A second plume impingement study was conducted at the Hogback Ridge (HBR) near Farmington, New Mexico during October 1982. The HBR is a long, roughly 90-m tall ridge with a gap at the San Juan River. Three flow visualization and 11 multi-hour, dual-tracer gas experiments were conducted. The experimental methods were similar to those used and tested at CCB:

- releases of two tracer gases (SF_6 and CF_3Br) and oil fog using a mobile crane and a tower as source platforms,
- fixed meteorological measurements obtained by four instrumented towers, two monostatic acoustic sounders, one Doppler acoustic sounder, and three optical crosswind anemometers,
- one tether sonde each at the source location and on the upwind face of the HBR,
- ground-level tracer gas concentrations, and
- plume dispersion documentation by lidar measurements, videotapes, and time-exposure photographs.

The meteorological data were archived and displayed by an array of onsite minicomputers. The availability of real-time information on ambient meteorological conditions and the flexibility of releasing oil fog and tracer gas at a variety of heights and locations enabled selective placement of source positions to obtain useful information for model development purposes. The real-time information was supplemented by near real-time lidar data and by prompt development of plume photographs. Approximately 86 hours of dual-tracer gas experiments were conducted during the HBR field experiments.

A preliminary examination of the unedited meteorological, tracer gas concentration, and photographic data indicates that the field study was successful. The new HBR experimental data base will provide a good basis for testing and extending the CTMD modeling approaches and the dividing streamline concept for two-dimensional ridges. Preliminary analyses and observations in the field suggest that plumes released above H_c tended to flow over the ridge and plumes below H_c tended to flow along the ridge. Occasionally at night, the elevated plume mixed to the ground upwind of and on the ridge. The mixing was apparently caused by turbulence produced during breakdown of the stable boundary layer.

CONCLUSIONS

Results from the analyses undertaken to date on the refined CCB data base are leading toward a complex terrain modeling system with two major flow components. The usefulness of the critical height (H_c) as a parameter to differentiate the two distinct flow regimes has been amply demonstrated at CCB. Plume trajectories well below and well above H_c are consistent with low and high Froude number flow theory, respectively. The behavior of trajectories near H_c is difficult to describe analytically, but in practice the plume behavior on the windward face of the hill appears amenable to low Froude number modeling.

Because H_c is a critical parameter in modeling stable flow in complex terrain, the use of this two-model approach in a regulatory setting will require truly representative meteorological information. On-site vertical profiles of wind and temperature are necessary because there is no substitute for H_c to differentiate between impingement cases and near-neutral flow cases.

The modifications made to the models facilitate their applicability to sites other than CCB, and increase their usefulness for estimating concentrations over several hours. The Lift Model now incorporates a measure of the crosswind aspect ratio of the terrain feature. The Wrap Model estimates concentrations at more than one (stagnation) point across the hill surface.

The Wrap Model impingement estimates (and, in fact, the observed concentrations) are very dependent on the actual horizontal wind direction distribution when the winds are light and variable. When the plume is released above H_c , concentrations over the top of the hill are extremely sensitive to the size of σ_z . Therefore, on-site meteorological input is required at levels representative of plume height.

Initial analysis of the HBR data base suggests that the concept of a critical dividing-streamline height is also appropriate for stable flows toward a two-dimensional ridge. Tracer gas released below H_c dispersed in a highly variable, "blocked" flow and produced relatively large ground-level concentrations on the windward face of the ridge. Tracer gas emitted above H_c dispersed in a flow that traveled over the ridge and produced peak ground-level concentrations near the ridge crest and on its lee side.

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